AS 10/517,808

(12) UK Patent Application (19) GB (11) 2 212 274 (13) A

(43) Date of A publication 19.07.1989

(21) Application No 8826263.9

(22) Date of filing 09.11.1988

(30) Priority data
(31) 874942 (32) 09.11.1987 (33) FI

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(51) INT CL⁴
G01P 15/125

(52) UK CL (Edition J)
G1N NAED N1D5 N7Q N7T1A
U1S S2151

(56) Documents cited
GB 2194341 A GB 2178856 A

(58) Field of search
UK CL (Edition J) G1J, G1K, G1N NACA NAED
NAFE NAGB NAGC
INT CL⁴ G01P

(54) **Capacitive accelerometer and its fabrication method**

(57) The accelerometer comprises two side electrode structures (15) incorporating fixed side electrodes (4) and, arranged between the fixed side electrodes, a centre electrode structure (16) which incorporates at least one centre electrode (17). The centre electrode structure (16) comprises a planar body element (3) providing a wall which, with the side electrode structures, defines a cavity. In the cavity a movable electrode portion (1) of centre electrode (17) is supported in cantilever by a stem portion (2) projecting from the wall. The device is symmetrical about plane S. The centre electrode structure is processed by etching a groove penetrating the body element (3) in a U-shape and delineating the cantilever beam-like centre electrode (17). Portion (1) of the centre electrode (17) is formed thinner than the wall section of the body element (3) so that electrode gaps (7) are formed between the side electrodes (4) and the centre electrode (17). The stem section (2) of the centre electrode structure (16), integral with the body element (3), is essentially thinner than the portion (1) in order to obtain a flexible centre electrode (17). The transducer construction in accordance with the invention is easily manufactured in mass production.

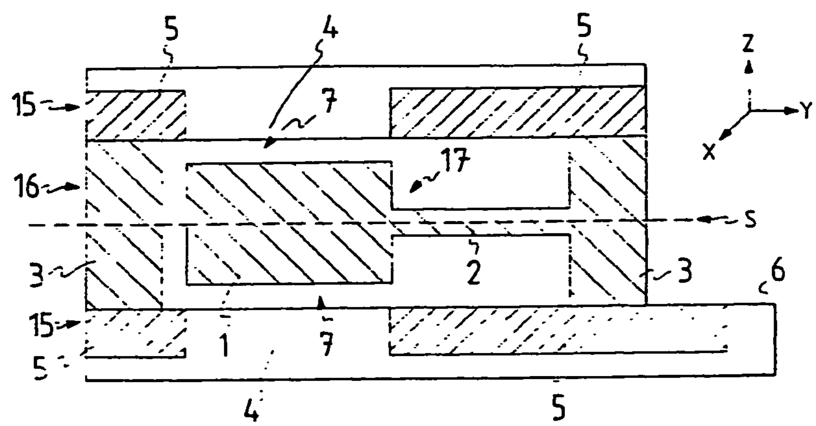

Fig.1

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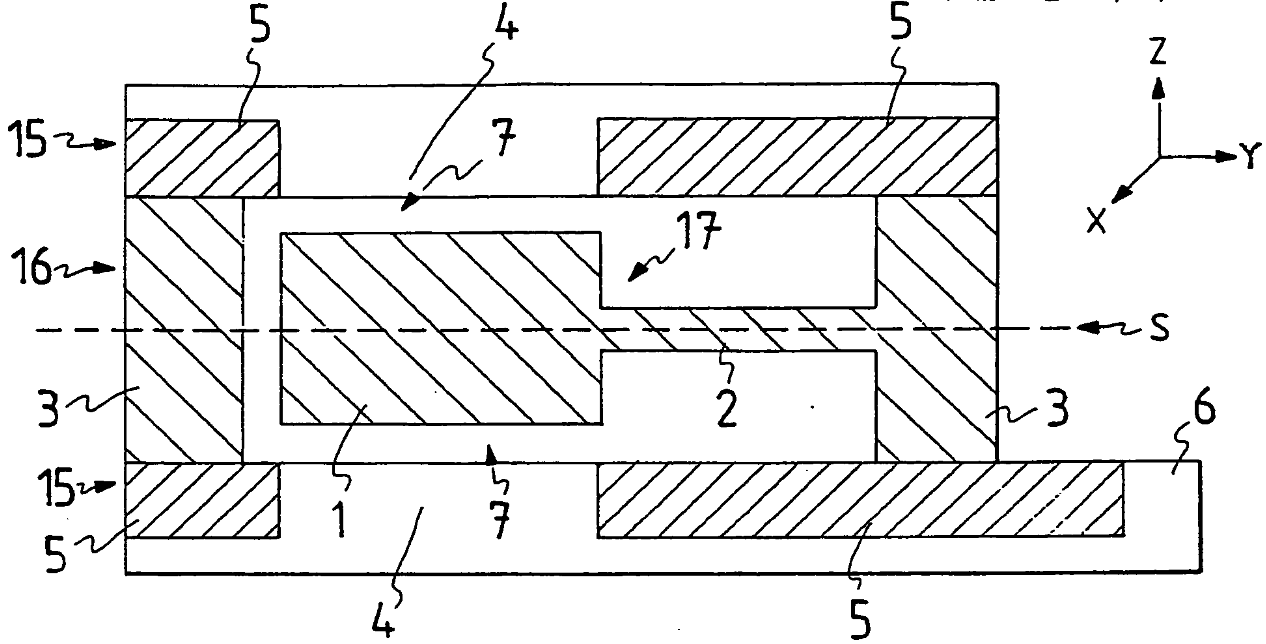

Fig.1

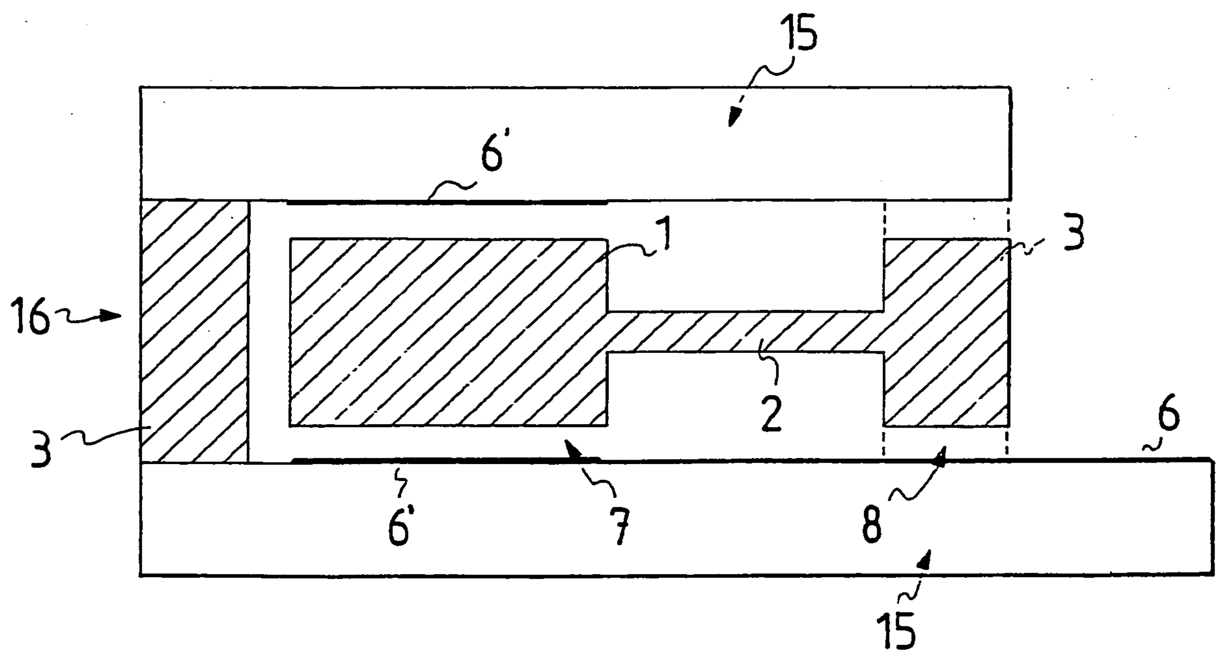

Fig.2

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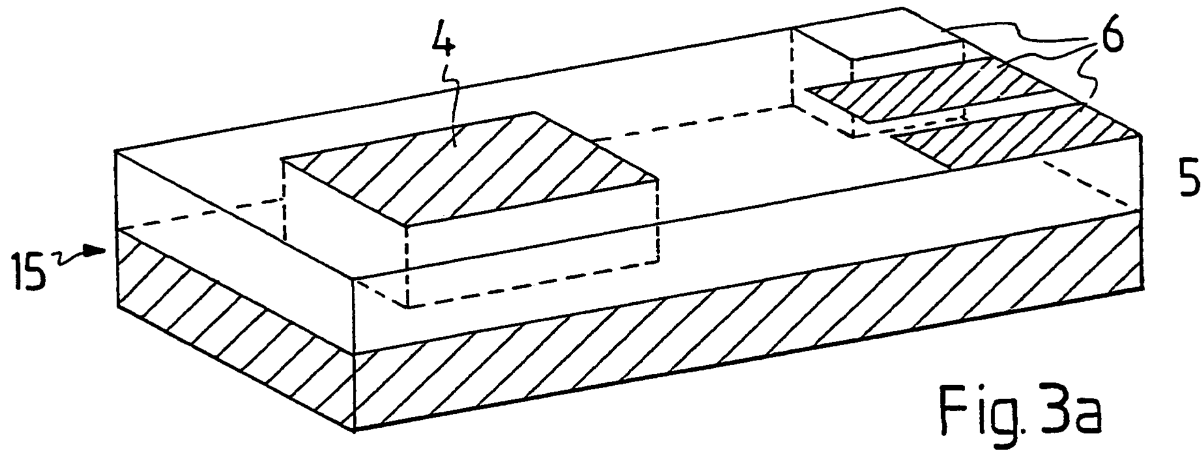

Fig. 3a

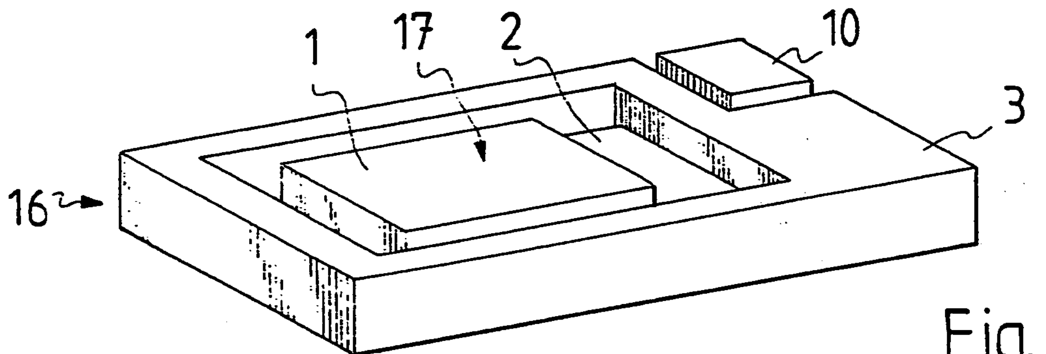

Fig. 3b

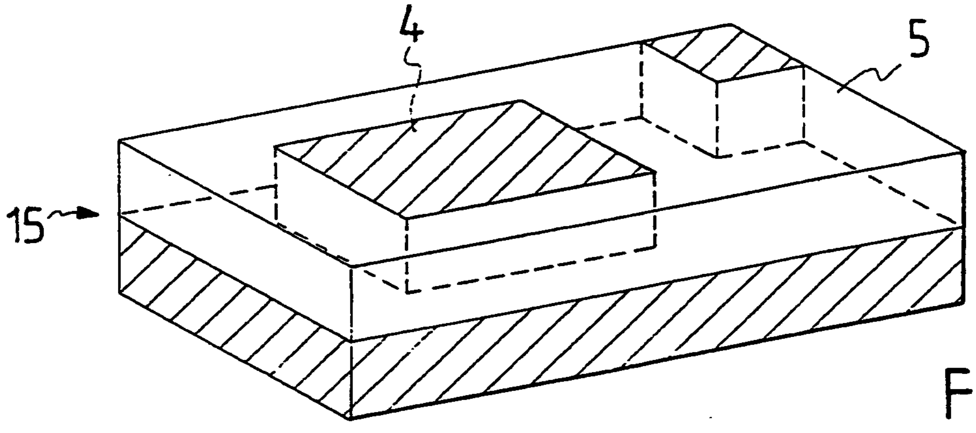

Fig. 3c

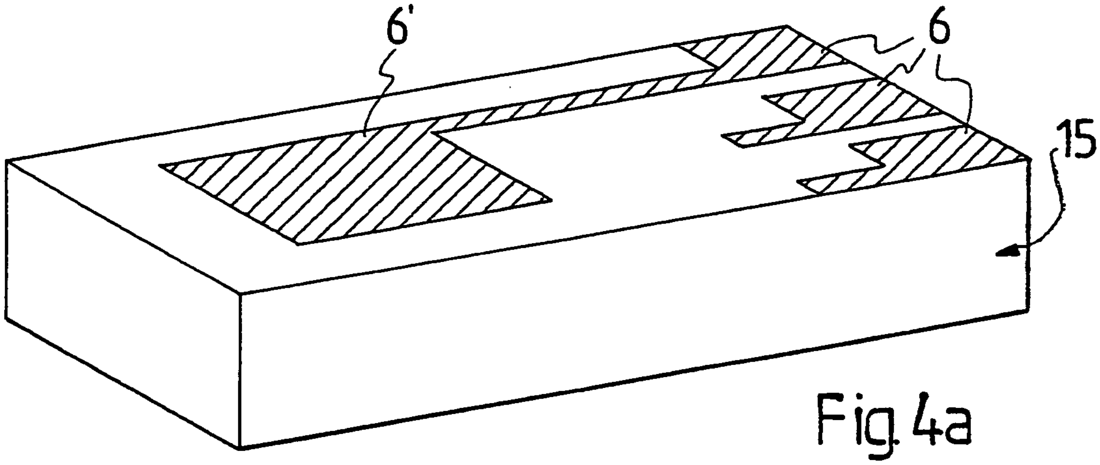

Fig.4a

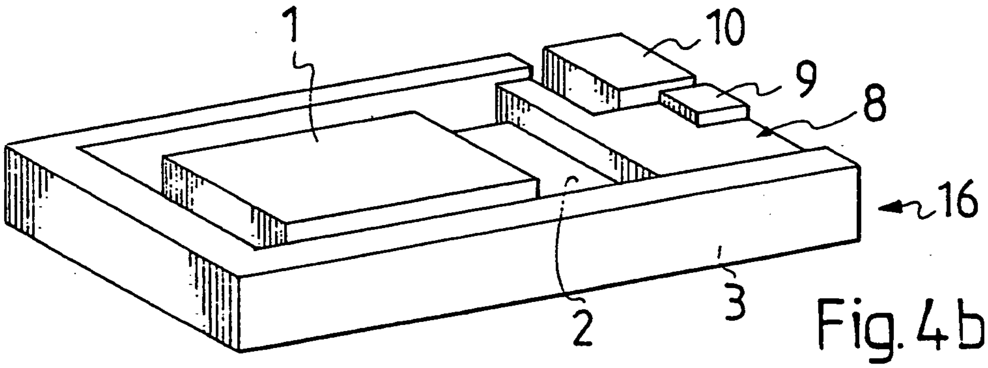

Fig.4b

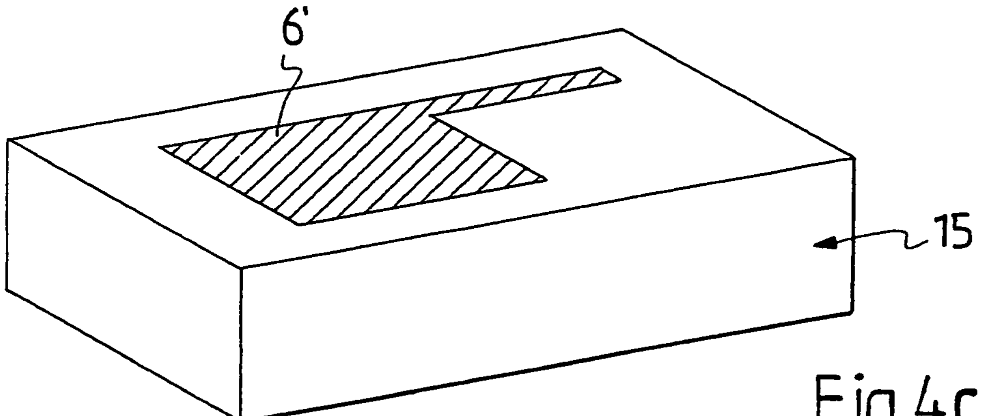

Fig.4c

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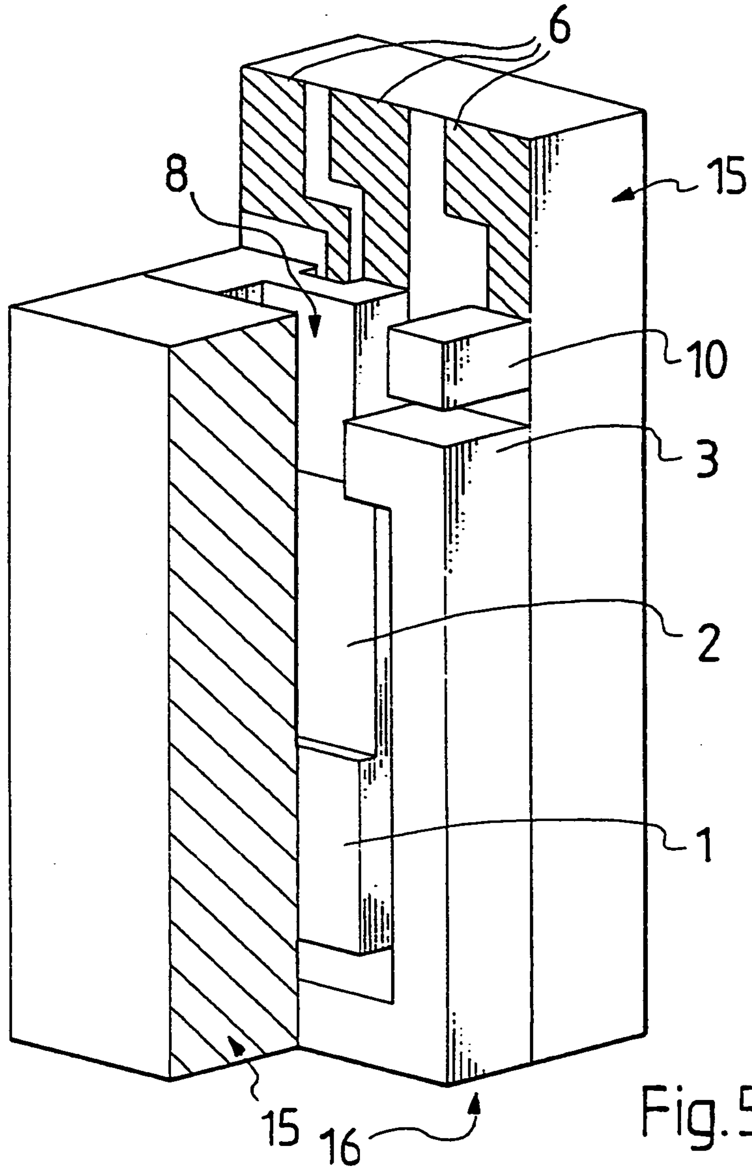

Fig.5

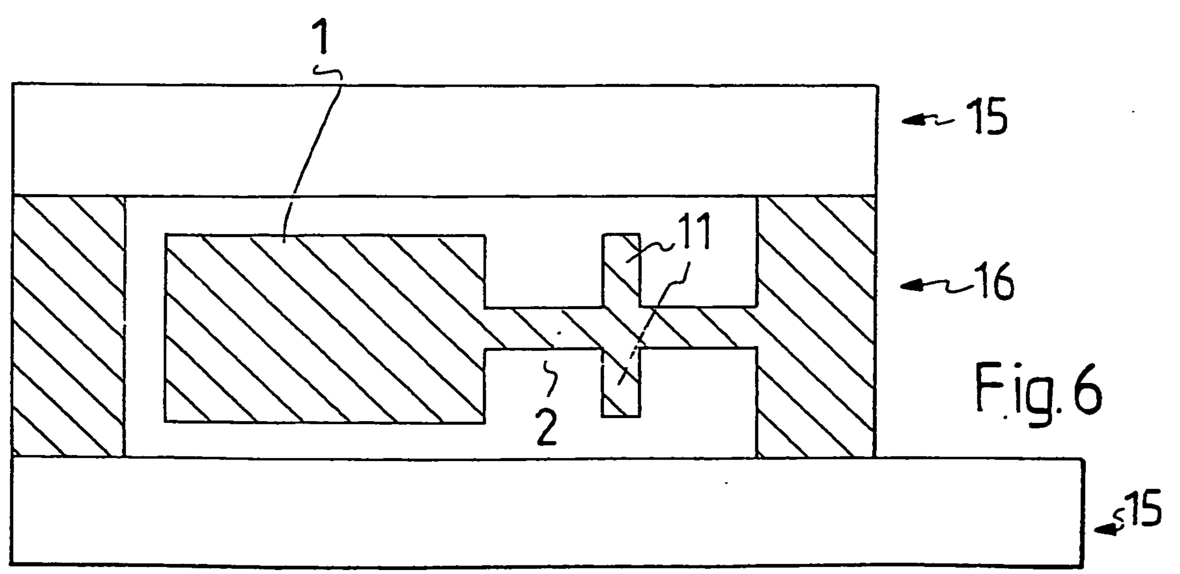

Fig.6

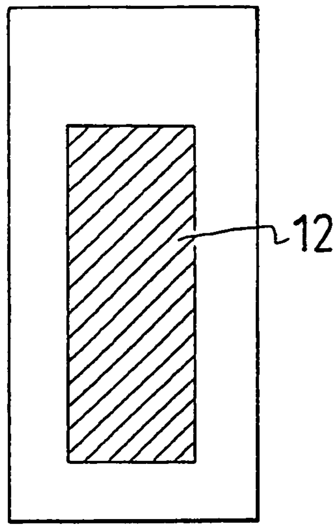

Fig. 7a

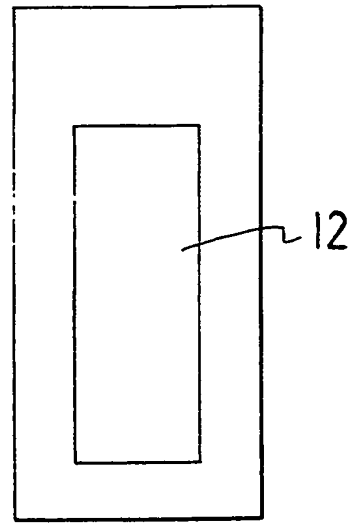

Fig. 7b

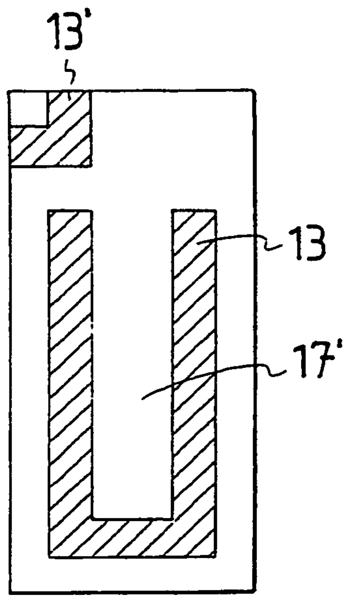

Fig. 8a

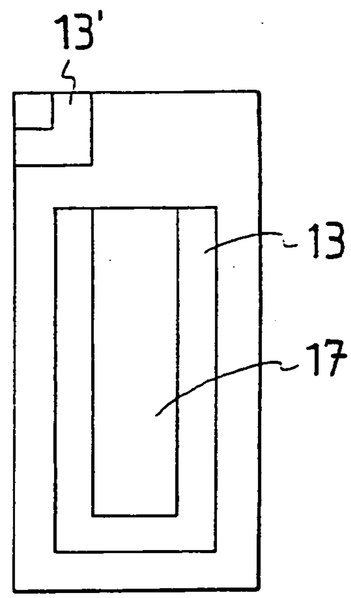

Fig. 8b

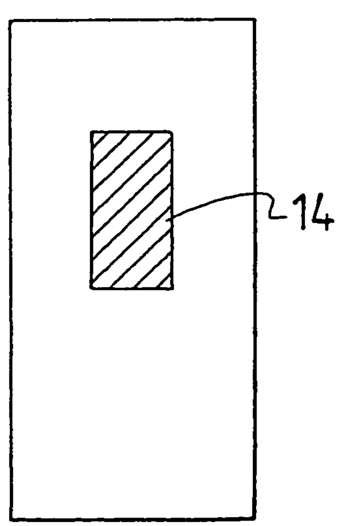

Fig. 9a

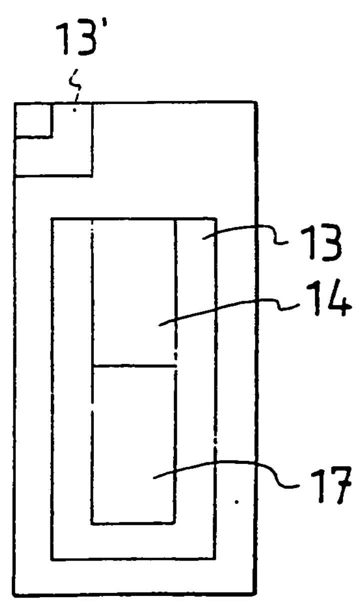

Fig. 9b

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Capacitive accelerometer and its fabrication method

The present invention relates to a capacitive accelerometer in accordance with the preamble of claim 1.

The invention also concerns a method for the fabrication of an accelerometer.

The accelerometer is actually a miniature-size force sensor, whose main application, however, is in the detection of acceleration. The device may also be applied for other use, e.g., in the detection of inclination angle.

Miniature size accelerometers known in the art are mostly based on the piezoelectric or piezoresistive operating principle.

A piezoelectric crystal develops a surface charge whose magnitude is dependent on the force applied to the surface. This charge is then measured using a charge-sensitive amplifier. The high input impedance of the amplifier used in the measurement makes the amplifier susceptible to electrostatic disturbance. Charges developed on the surface are spontaneously discharged via surface leakage currents making it impossible to use this accelerometer type for the measurement of static or low-frequency accelerations.

A piezoresistive accelerometer is typically made of a semiconductive material, e.g., of silicon, into which resistors are diffused in appropriate crystal directions. When the crystal is flexed, the induced stresses cause changes in resistance values allowing the magnitude of flexure to be detected. The magnitude of flexure is proportional to the force applied and, consequently, to the acceleration.

Miniature-size piezoresistive can be manufactured of, e.g., silicon using the fabrication methods of microelectronics and micromachining. In order to obtain the maximum sensitivity, the stress maxima must be placed to the area of the resistors. Therefrom follows that the displacement of the elastic part becomes excessively large in amplitude in relation to the thickness of the structure, in addition to which, sensitive accelerometers must be provided with auxiliary weights acting as the seismic masses of the accelerometer, because silicon itself is relatively light in density. The fabrication of the auxiliary masses makes the process difficult to implement. Further, the piezoresistive accelerometer is far more sensitive to temperature excursions than, e.g., a capacitive accelerometer. Furthermore, the so-called gauge factor is lower for the piezoresistive accelerometer than for the capacitive accelerometer.

Monocrystalline silicon has been used in the fabrication of accelerometers since the late 1960's. Some of these solutions are published in scientific articles and some also patented. Piezoresistive accelerometers are described, i.a., in the following publications:

[1] L.M. Roylance and J.B. Angell, "A batch fabricated silicon accelerometer," IEEE Trans. on Electron Devices, ED-26, pp. 1911...1920 (1979)

[2] W. Benecke et al., "A frequency selective, piezoresistive silicon vibration sensor," Transducers '87, pp. 406...409 (1987)

[3] M. Tsugai and M. Bessho, "Semiconductor accelerometer for automotive controls," Transducers '87, pp. 403...405 (1987)

[4] E.J. Evans, US pat. 3,478,604 (1968)

[5] A.J. Yerman, US pat. 3,572,109 (1971)

The constructions in accordance with the publications [4] and [5] concern an accelerometer of the "flexible cantilever" type.

Respectively, the capacitive accelerometers are described in the following publications:

[6] H.W. Fischer, US pat. 3,911,738 (1975)

[7] W.H. Ficken, US pat. 4,009,607 (1977)

[8] F.V. Holdren et. al., US pat. 4,094,199 (1978)

[9] H.E. Aine, US pat. 4,144,516 (1979)

[10] K.E. Petersen et al., US pat. 4,342,227 (1982)

[11] R.F. Colton, US pat. 4,435,737 (1984)

[12] F. Rudolf, US pat. 4,483,194 (1984)

[13] L.B. Wilner, US pat. 4,574,327 (1986)

Publication [6] describes an accelerometer using two capacitances without disclosing a physical construction.

Publication [7] is principally identical to publication [6] except for a different electrical implementation.

Publication [8] also deals with the dual capacitance principle of an accelerometer.

Publication [9] describes a micromechanical accelerometer, in which the seismic mass is suspended on leaf springs.

Publication [10] describes an accelerometer of the flexible cantilever type, in which the cantilever beam moves in the horizontal plane and has an electrically nonsymmetrical construction.

Publication [11] deals with an annular construction.

Publication [12] deals with a torsionally suspended plate, in which the capacitance is placed only one side of the plate.

Publication [13] describes a construction in which the seismic mass is suspended on a membrane spring. The aim of the present invention is to overcome the drawbacks of the aforementioned prior art technology and to provide a completely novel type of capacitive accelerometer and a method for its fabrication.

The invention is based on constructing the accelerometer of the capacitive type from two capacitors, which have a common moving electrode acting as the seismic mass of the accelerometer. The center electrode forms a monolithic construction with a beam fabricated of the same material. It is possible to use one or several of these elastic members. Due to an applied acceleration, the seismic mass is displaced by a few micrometers, and the displacement is detected from changes in the capacitance values. The accelerometer construction is two-sided and symmetrical.

More specifically, the accelerometer in accordance with the invention is characterized by what is stated in the characterizing part of claim 1.

Furthermore, the fabrication method in accordance with the invention is characterized by what is stated in the characterizing part of claim 5.

The construction in accordance with the invention offers the following benefits:

- the capacitive operating principle attains a high sensitivity $\Delta C/C$ at a small displacement of the seismic mass,

- due to the symmetric construction, the accelerometer has an extremely low uncompensated temperature sensitivity,

- as the seismic mass is of the same material with flexible member, e.g., of silicon, an auxiliary seismic mass is unnecessary,

- the accelerometer damping factor is alterable by fabricating grooves on the capacitor electrodes or by leaving a proper pressure into the accelerometer construction during the fabrication process,

- the capacitance changes are symmetric about the zero value of acceleration,

- the accelerometer is capable of being fabricated in mass production,

- the accelerometer has a remarkably high overload tolerance, because the seismic mass is displaced only by a few micrometers before being backed by the side electrodes.

In the following, the invention will be examined in more detail by means of the exemplifying embodiments in accordance with the attached drawings.

Figure 1 shows a longitudinally sectioned side view of an accelerometer construction in accordance with the invention.

Figure 2 shows a longitudinally sectioned side view of another accelerometer construction in accordance with the invention.

Figures 3a...3c show in perspective view the different parts of the accelerometer construction illustrated in Fig. 1.

Figures 4a...4c show in perspective view the different parts of the accelerometer construction illustrated in Fig. 2.

Figure 5 shows a partially longitudinally sectioned perspective view of the accelerometer construction illustrated in Fig. 2.

Figure 6 shows a longitudinally sectioned side view of a third accelerometer construction in accordance with the invention.

Figure 7a shows a top view of a first masking phase of the accelerometer construction in accordance with the invention.

Figure 7b shows a top view of final result obtained by the masking phase illustrated in Fig. 7a.

Figure 8a shows a top view of a second masking phase of the accelerometer construction in accordance with the invention.

Figure 8b shows a top view of final result obtained by the masking phase illustrated in Fig. 8a.

Figure 9a shows a top view of a third masking phase of the accelerometer construction in accordance with the invention.

Figure 9b shows a top view of final result obtained by the masking phase illustrated in Fig. 9a.

The accelerometer according to the invention may be fabricated of, e.g., monocrystalline silicon using conventional methods known in micromechanical fabrication. Figure 1 illustrates the basic construction of the accelerometer. The accelerometer may be hermetically sealed so that the accelerometer case may be sealed filled with gas in an appropriately low underpressure. The pressure of the filling gas may be varied to obtain desired damping factor of the accelerometer's seismic mass. The filling gas used may be, e.g., dry air. An appropriately selected damping factor results in an advantageous frequency response of the accelerometer.

However, a simpler construction of the accelerometer is attained by making the accelerometer open as illustrated in Fig. 2 so that the internal gas pressure of the accelerometer is equal to the ambient pressure. Communication of the internal gas space with the ambient takes place via a channel 8. Then, the damping factor of the seismic mass is, however, extremely high, allowing this kind of an accelerometer to be used only at low frequencies (that is, a few Hz) and static acceleration measurements alone.

Figure 1 illustrates the hermetically sealed accelerometer construction. The accelerometer is a layered structure comprising of planar, electrically interconnected side electrode structures 15, and between them, a parallel aligned center electrode structure 16, whose seismic mass 1 is provided by the tip of a cantilever beam 17. The cantilever beam 17 is formed into the center electrode structure 16 by fabricating into the beam a U-shaped groove, which extends through the entire structure of the center electrode 16. Additionally, material has been removed from

the beam 17 in order to form a gap 7 which provides for a capacitance, and furthermore, the width of a stem section 2 of the beam 17 has been reduced in order to obtain flexibility at this section. Thence the integral center electrode structure 16 comprises the beam 17, which further comprises the seismic mass 1 and the flexible stem section 2 as well as an accelerometer body element 3 surrounding the cantilever beam 17. The seismic mass 1 is advantageously fabricated a few micrometers thinner than the body element 3. The center electrode structure 16 may be fabricated of, e.g., the same monocrystalline silicon. The accelerometer capacitances are formed between the common moving electrode 1 of the center electrode structure 16 and the fixed side electrodes 4 of the side electrode structures 15. The side electrodes 4 are fabricated of, e.g., mono-crystalline silicon by etching the surfaces corresponding to an insulating layer 5 so as to leave a raised area in the silicon at the seismic mass 1 as well as at a bonding area 6. The insulat-ing layer 5 may be of, e.g., glass. The glass-coated area 5 and the body element 3 may be hermetically bonded to each other using, e.g., anodic bonding. The construction of the center electrode structure 16 is mirror-symmetric in relation to a plane s (xy-plane) shown in Fig. 1. The seismic mass 1 is movable in the z-direction.

The accelerometer construction according to Fig. 1 is illustrated in detail in Figs. 3a...3c. The upper diagrams 3a and 4a of Figs. 3 and 4 are shown in inverted position to make metallized areas 6 and 6' as well as the silicon area 4 better visible.

Figure 2 illustrates an open accelerometer construction. This construction differs from the closed construction in the following details:

- the side electrode structure 15 is fabricated entirely of glass having its surface covered by metallized areas 6 and 6' for the electrical functions of the accelerometer,

- the metallization 6 is placed running in a channel 8 with the purpose of preventing the short-circuiting of the metallization 6 to body element 3.

The accelerometer construction according to Fig. 2 is illustrated in detail in Figs. 4a...4c. In both constructions shown, the electrical contact areas 6 are preferably fabricated in the same plane thus making it necessary to use an electrical feed-through 10 shown in Figs 3 and 4. This detail is of the same material as the body element 3, however, electrically insulated from the body element. The structure of the element 10 is further detailed in Fig. 5. The purpose of a bump 9 shown in Fig. 4b is to form an electrical contact from the body element 3 to the middle contact area 6. The accelerometer layout is illustrated in Fig. 5.

Shock resistance of the accelerometers may be improved by etching the flexible element 2 so as to leave into it such protrusions 11 as shown in Fig. 6 that prevent an excessive flexure of the element 2 under a heavy shock. The dimensioning of the accelerometer is strongly dependent on the desired sensitivity and capacitances. Typical dimensions are, e.g., 2 x 0.5 x 4 mm^3 for the seismic mass 1 and 2 x 0.07 x 4 mm^3 for the cantilever beam 2. The external dimensions of the accelerometer are about 4 x 3 x 12 mm^3 (width x height x length).

The fabrication phases described in the following are applicable for processing both sides of such base material,

which is a mono-crystalline semiconductor, e.g., a silicon wafer polished on both sides.

1. Both sides of the silicon wafer are oxidized to a depth of approx. 250 nm. The wafer thickness may be, e.g., 500 µm.

2. The wafer is coated with a photoresist and exposed as illustrated in Fig. 7a for center electrode areas 12, from which the oxide is to be etched away. Fig. 7 illustrates one silicon chip.

3. Next, the center electrode area 12 illustrated in Fig. 7b is etched to a depth of approx. 4 µm in, e.g., aqueous solution of KOH.

4. The oxide layer of the wafer is etched away using buffered HF, and the wafer is oxidized to a depth of approx. 0.8 µm.

5. The wafer is coated with a photoresist and exposed by the edges of the center electrode area 12 for an edge area 13 and a contact area 13' illustrated in Fig. 8a, from which areas oxide is removed. The photoresist is removed.

6. The areas 13 and 13' are etched to a depth of approx. 50 µm, whereby a center electrode pattern 17' is formed according to Fig. 8b.

7. The wafer is re-coated with a photoresist and exposed by the stem section of the center electrode pattern 17' for an area 14 according to Fig. 9a, from which area oxide is removed.

8. The wafer etching is continued in, e.g., an aqueous solution of KOH until a desired depth of the area 14 is attained, typically down to 40...100 µm, whereby a penetration of the area 13 occurs as illustrated in Fig. 9b.

This process results in the element 16 according to Fig. 3b.

The side electrode structures 15 according to Figs. 3a and 3c are fabricated using the above described technique by etching one surface of the silicon wafer to a depth of approx. 150 µm leaving only the small (hatched) area 4 shown in Figs. 3a and 3c, together with the area 6 (hatched) electrically communicating with the area 4, to the original height. Next, the etched surface of the wafer is coated by melting an appropriate glass layer of, e.g., Schott Tempax, Corning 7070, or Corning 7740 grade glass, which is abraded and polished to the same level with the original surface of the wafer. This method is known in the art from US patent 4,597,027 (A. Lehto). The glass-coated wafer is then processed for the metallizations 6 using a lift-off method or an etching process. These methods are conventional processes, and their detailed description is omitted. Finally, all three wafers are bonded together using the so-called anodic bonding in an appropriate pressure. The pressure level used depends on the desired damping factor of the accelerometer being typically in the order of a few hPa. A detailed description of applied methods (as well as of other methods) is to be found in the book Ivor Brodie and Julius J. Muray, The Physics of Microfabrication, Plenum Press, New York, 1983.

The center electrode structures 16 according to Figs. 4a...4c are fabricated using almost identical methods to those described above. The difference lies in an area, which is made wider during the 4 µm etching phase at the sections of the channel 8 and the contact area 9.

The center electrode structures 15 according to Figs. 4a...4c are fabricated of glass, e.g, of Schott Tempax, Corning 7070, or Corning 7740 grade glass. The areas 6 and 6' are metallized using the method described in the

foregoing. The accelerometer assembly is carried out using anodic bonding in a normal ambient pressure.

In both accelerometer constructions, the wafers may be cut by breaking with the help of precut grooves.

CLAIMS

1. A capacitive accelerometer of silicon material comprising two plate-like side electrode structures each of which comprises a side electrode, and a centre electrode structure including a body element in the form of a boundary wall, disposed between the two side electrode structures which are mounted to the body element via an electrically insulating layer, to define therewith a chamber within which is a centre electrode joined to and encircled by the wall and including a stem section providing cantilever support for a mass having a thickness approaching the thickness of the body element so as to define an electrode gap between each side electrode and the mass, the central electrode being symmetrical about a centre plane defined by the spaced side electrode structures.

2. A capacitive accelerometer of silicon material comprising two mutually spaced, parallel aligned, essentially plate-like planar side electrode structures positioned face to face, which comprise fixed side electrodes and a uniform, essentially plate-like centre electrode structure arranged between the side electrode structures which centre electrode structure comprises a body element adjoining to the side electrode structures and at least one centre electrode, placed to the vicinity of the side electrodes and comprising a stem section and a tip so that the stem of the centre electrode joins the centre electrode to the body element, which encloses the centre electrode from the sides, whereupon the stem section is essentially

thinner than the tip, wherein the centre electrode structure is symmetrical about the centre plane(s) of the side electrode structures, the centre electrode has beam-like shape and is surrounded by a groove extending through the body element in a U-shape, the tip of the centre electrode has a thickness approaching that of the body element so that thin electrode gaps, with a spacing determined by the thickness of the tip are formed between the side electrodes and the centre electrode, and wherein the side electrode structures are mounted via an electrically insulating layer in a hermetically sealed manner onto the body element of the centre electrode structure, whereby each centre electrode remains into a hermetically sealed closed chamber and the electrode structures are in normal conditions galvanically isolated from each other when no external connections exist.

3. An accelerometer according to claim 1 or claim 2, wherein the centre electrode structure has a rectangular shape.

4. An accelerometer according to any preceding claim, wherein the centre electrode structure is processed to form a columnar, electrically conductive connecting structure electrically isolated from the rest of the centre electrode structure, whereby bonding areas of the side electrodes are arranged into the same plane.

5. An accelerometer according to any preceding claim wherein the body element, the stem and the mass of the centre electrode structure are formed integrally, preferably from a homogeneous monocrystalline semiconductor chip.

6. An accelerometer according to any preceding claim wherein said chamber containing the centre electrode is hermetically sealed; the gas pressure or vacuum being selected according to the frequency response required.

7. A method for manufacturing a capacitive accelerometer in accordance with any preceding claim comprising fabricating the centre electrode structure from a homogeneous monocrystalline semiconductor chip and mounting the side electrodes in a hermetically sealed manner to the centre electrode structure.

8. A method according to claim 7 wherein the centre electrode structure is fabricated by etching both sides of the chip initially in a central electrode area, further etching edge areas of the central electrode area and subsequently further etching the said edge areas and the stem section area from both sides of the chip until the chip is etched through in the edge area leaving the stem section at a desired thickness to provide cantilever support for the said mass.

9. A method for fabricating a capacitive accelerometer in which method two side electrode structures comprising fixed side electrodes are formed, and a centre electrode structure comprising a centre electrode is arranged between th side electrode structures comprising the steps of fabricating the central electrode structure from a homogeneous monocrystalline semiconductor chip by etching a central electrode area to both sides of the chip centre section, further etching edge areas of the central electrode area at

both sides of the semiconductor chip so as to leave the remainder of the centre electrode area as a beam-like centre electrode pattern of a thickness and remaining integral with the unetched semiconductor chip, etching a stem section and the edge areas of the centre electrode pattern at both sides until the edge area is etched through and the stem section attains a desired thickness, and mounting the side electrodes in a hermetically sealed manner to the centre electrode structure.

10. A method according to any of claims 7 to 9 wherein in conjunction with the mounting of the side electrodes to the centre electrode structure, there is arranged a proper gas pressure into a space hermetically enclosed by the side electrodes in order to obtain an advantageous frequency response of the sensor.

11. A capacitive accelerometer constructed and arranged substantially as hereinbefore described with reference to and as illustrated in the accompanying drawings.

12. A method for manufacturing a capacitive accelerometer substantially as hereinbefore described with reference to the accompanying drawings.

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